Heavy Ions — Prospects at the LHC

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This is a review of the physics prospects for relativistic heavy ion collisions in the CERN Large Hadron Collider. The motivation for the study of superdense matter created in relativistic heavy ion collision is the prospect of observing a novel state of strongly interacting matter, the quark-gluon plasma. Experiments at the CERN Super Proton Synchrotron (SPS) and the Relativistic Heavy Ion Collider (RHIC) at Brookhaven have yielded important clues of the characteristic signatures of this new state. The LHC will extend the range of energy densities that can be explored and facilitate the observation of plentiful hard probes (jets, heavy quarks) of the properties of the dense matter.

1 The Quark-Gluon Plasma

Computer simulations of lattice QCD predict that the properties of strongly interacting matter change drastically at an energy density of the order of 1 GeV/fm^3 or, for baryon symmetric matter, at the temperature $T_c = 165 \pm 10$ MeV [1]. According to the best available calculations, this transition is not a true (discontinuous) phase transition at zero net baryon density, or baryochemical potenial $\mu_B = 0$, but at rapid crossover from a low-temperature phase dominated by hadrons into a high-temperature phase best characterized as a strongly interacting plasma of quarks and gluons. The transition is seen as a steep rise in the vicinity of T_c in the effective number of degrees of freedom g_D defined as $\epsilon = g_D \pi^2 T^4/30$, where ϵ is the energy density and T the temperature (see Fig. 1).

For nonzero net baryon density the crossover narrows further and is expected to become singular at a critical point (T_{cr}, μ_{Bcr}), beyond which the phase transition is of first order. Lattice calculations of the location of this critical point have become possible only within the past two years; the predictions are still quite uncertain with a current best estimate of (160, 360) MeV [3,4]. The change in the properties of the matter at the critical line $(T_c(\mu_B), \mu_B)$ is characterized by the disappearance of the vacuum condensate $\langle \bar{\psi}\psi \rangle$ of light quarks, accompanied by the screening of the force between colored quanta.

Among the proposed signatures for the formation of a quark-gluon plasma in relativistic heavy ion collisions are [5]:

– Effects of the latent heat in the (ϵ, T) relation;

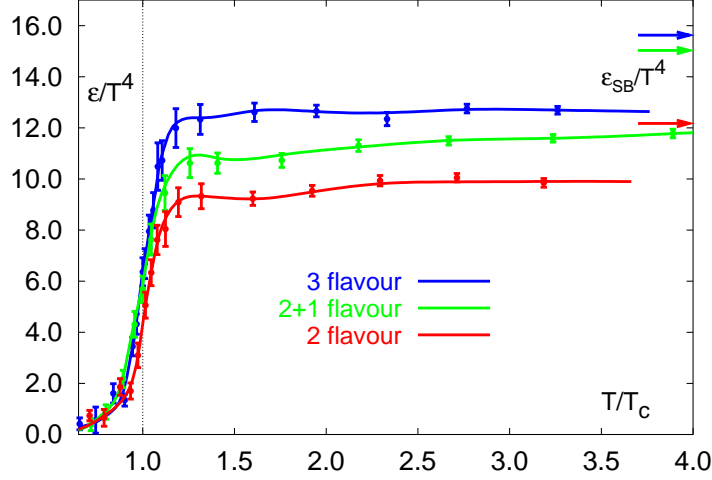– Enhancement of s-quark production;

Fig. 1. Energy density in QCD with 2 and 3 quark flavors, showing a transition temperature T_c between a hadronic gas and a plasma of quarks and gluons (from [2]).

- Disappearance of light hadrons, especially the ρ^0;

- Bulk hadronization by quark recombination;

- Disappearance of $(c\bar{c})$ and $(b\bar{b})$ bound states;

- Large energy loss of fast partons (jet quenching);

- Thermal $\ell^+\ell^-$ and γ radiation;

- Critical fluctuations (momentum, baryon number);

- Collective vacuum excitations.

Many of the signatures have been observed and studied in heavy ion collisions at the SPS at CERN and the RHIC at Brookhaven. The experiments with Pb+Pb collisions at $\sqrt{s_{NN}} = 17.6$ GeV at the SPS showed a significant enhancement of the production of strange baryons and antibaryons, increasing with their strangeness content [6], a suppression in the production of the J/Ψ which grows with the centrality of the collision [7], and a strong enhancement of low-mass dilepton production below the ρ^0 resonance, presumably caused by a broadening (or mass shift) of the ρ-meson in dense matter [8]. In recent years, indications of a plateau in the spectral slopes of K-mesons over the range of energies available at the SPS was also found [9].

In its first three years of running, the RHIC program confirmed the strong enhancement of strange baryon production and found new, unexpected evidence for

the formation of hadrons out of a bulk deconfined phase by quark recombination [10]. It also discovered the strong suppression of high-p_T hadrons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV due to final state interactions [11]. This effect (often called "jet quenching") is understood to be a result of the energy loss of hard scattered partons on their passage through the created matter by gluon radiation [12]. For a detailed evaluation of the results obtained by the experiments at RHIC, see the collaboration white papers [13].

2 Heavy Ions in the LHC

At LHC ^{208}Pb nuclei will collide with a center-of-mass energy $\sqrt{s} = 5.5$ TeV. The almost 30-fold increase in center-of-mass energy over RHIC will lead to a much higher initial energy density and to an even faster equilibration. Higher energy density and increased lifetime of the deconfined phase will enhance the role of the QGP phase over final state hadronic interactions. Furthermore, jets and high-p_T hadrons with transverse momenta of 100 GeV/c and more will become available [14]. Finally, c and b quarks will become plentiful probes at the LHC energy [15].

I will next discuss what we have learned so far from RHIC experiments about hard QCD probes and give some predictions and extrapolations that have been made for the LHC energy. Before doing so, however, it is important to review the physics of parton saturation, which is indispensible when one wants to understand the initial conditions for nuclear collisions at the LHC.

2.1 Parton saturation

The physics of saturation of the nuclear parton distributions [16] at small values of the Bjorken variable x has been the subject of intense research over the past decade [17,18]. Because of its reach to much lower values of x ($10^{-4} - 10^{-5}$), the LHC will be an ideal testing ground for saturation physics. The concept of parton saturation is based on the notion that the gluon distribution in a hadron or nucleus cannot continue to grow faster and faster at small x without violating unitarity. At some point, gluon fusion must balance the growth caused by gluon splitting. The scale at which the probability of interaction among the partons in the nuclear wave function approaches unity determines the saturation scale Q_s [16]:

$$\frac{xG_A(x, Q_s^2)}{\pi R_A^2} \frac{\alpha_s(Q_s^2)}{Q_s^2} \sim 1. \tag{1}$$

The universal form of the gluon distribution that emerges when saturation is reached has been called a *color glass condensate* (CGC). Fits to HERA and NMC data suggest that the saturation scale grows with nuclear size and decreasing x as [19]:

$$Q_s^2 = Q_0^2 (A/R_A)^\delta (x_0/x)^\lambda \tag{2}$$

with $\delta = 1.266$ and $\lambda = 0.288$. Since the charged multiplicity is related to the saturation scale by $dN_{\rm ch}/dy \sim \pi R_A^2 Q_s^2$, the saturation picture predicts a threefold increase in the multiplicity from RHIC to the LHC, or $dN_{\rm ch}/dy \approx 2000$ in

central Pb+Pb collisions [19,20] (see Fig. 2). The same calculations predict that the initially reached energy density of equilibrated gluon matter could be as high as 200 GeV/fm^3 at a time of 0.2 fm/c, corresponding to a temperature $T \approx 600$ MeV – almost twice the value initially reached at RHIC.
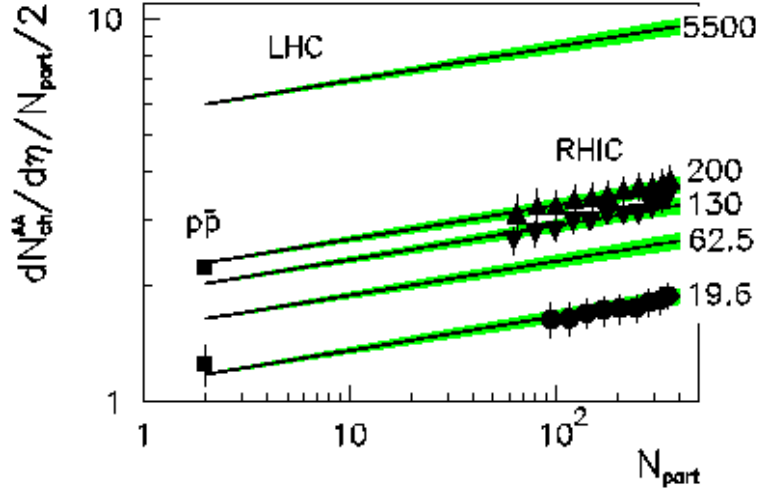

Fig. 2. Charged particle multiplicity per unit pseudorapidity predicted by the gluon saturation model in coparison with SPS and RHIC data (from [19]).

2.2 Jet quenching

Jet quenching is the name for the suppression of hadrons emitted with large transverse momenta, due to the energy loss of the partonic progenitors on their passage through the dense quark-gluon plasma. The name is a bit of a misnomer, because the energy contained in the jet is not reduced, but only redistributed to smaller values of the fragmentation variable z and also in the angle with respect to the jet axis. The theory of this effect is now quite well developed [12]. The leading parton radiates gluons induced by soft scattering on the constituents of the medium. The radiated gluons, in turn, rescatter inside the medium, thereby increasing their relative transverse momentum k_T with respect to the primary parton. This secondary rescattering is peculiar to QCD (rescattering of photons is not important in QED unless the medium is very thick), and leads to a quadratic dependence of the energy loss ΔE on the path length L inside the medium. The effect can be expressed as a medium induced modification of the fragmentation function $D(z)$ and the angular jet profile [21,22].

It is predicted that jet quenching at the LHC is much larger than at the RHIC due to the much higher initial energy density of the medium. However, the amount

of suppression of the leading hadrons that can be reached even in the most extreme case is limited, because partons scattered near the nuclear surface will always escape with rather little energy loss. High-p_T hadron production then becomes essentially a surface effect [23]. As the energy density increases, the visible surface layer shrinks, and the suppression becomes less and less sensitive to the high density interior, rendering high-p_T hadrons a somewhat "fragile" probe of dense matter [24]. Individual predictions for the nuclear suppression factor R_{AA} vary somewhat [24-26] (see Figs. 3 and 4) but, generally, the suppression is not expected to be much stronger than at RHIC, where $R_{AA} \approx 0.25$ in central Au+Au collisions at the highest measured momenta ($p_T \approx 10$ GeV/c).
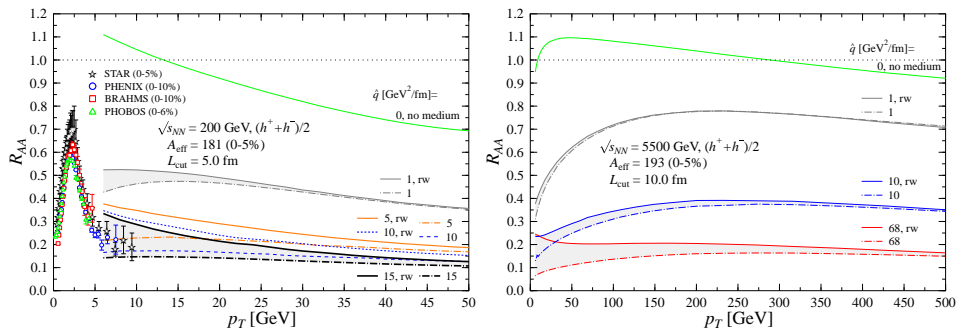

Fig. 3. Nuclear suppression factor R_{AA} for charged hadron in central Au+Au collisions at RHIC (left, with data) and Pb+Pb collisions at LHC (right) (from [24]).

In contrast to RHIC, it should be possible at the LHC to observe jets by calorimetry even in central Pb+Pb collisions. Together with the hadron spectrum within a jet, this would allow for a direct measurement of the modification of the fragmentation function and the energy loss of the leading parton. The concomitant broadening of the jet itself, when observed, would constitute a test of the energy loss mechanism by gluon radiation. Calculations, shown in Fig. 5, predict that hadrons with an intrinsic momentum $k_t < 1$ GeV/c should be suppressed, while hadrons with $k_t \sim 4$ GeV/c should be enhanced. Quantitative details depend on the jet cone definition [27] .

Other processes, which may become accessible for investigation at the LHC, are photon tagged jets [28] allowing for a direct measurement of the energy loss of the leading hadron and parton-to-photon conversion in the dense medium by Compton backscattering [29].

2.3 Parton recombination

One of the surprises found at RHIC was the relative enhancement – or rather, lack of nuclear suppression – of baryons in the momentum range 2 GeV/c $< p_T <$ 4 GeV/c [30,31]. This effect has been explained as the result of baryon formation by
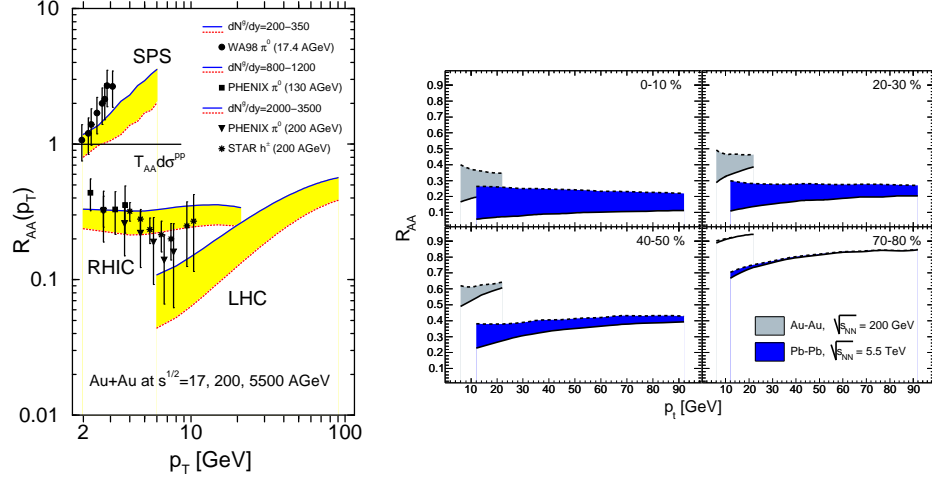
Fig. 4. Left: Nuclear suppression R_{AA} factor at SPS, RHIC and LHC energies for central Au+Au or Pb+Pb collisions (from [25]). Right: Centrality dependence of the nuclear suppression factor at RHIC and LHC (from [26]). The suppression disappears faster for peripheral collisions at LHC than at RHIC.

recombination of deconfined quarks leaving the quark-gluon plasma at the same moment [10,32,33]. It can be shown quite generally that recombination dominates over the leading twist mechanism of hadron formation, i. e. fragmentation, when the parton spectrum $w_i = e^{-P^+/T}$ is thermal, independent of the details of the hadron wavefunction [32]. The resulting hadrons exhibit the same thermal distribution, because the exponential factors from the constituents combine as

$$w_q(xP^+)w_{\bar{q}}((1-x)P^+) \quad = \quad e^{-P^+/T} \qquad \text{(mesons)}; \qquad (3)$$

$$w_q(x_1 P^+)w_q(x_2 P^+)w_q((1-x_1-x_2)P^+) \quad = \quad = e^{-P^+/T} \qquad \text{(baryons)}. \quad (4)$$

Only at sufficiently high p_T, where the parton spectrum turns into a power law, does fragmentation win out. Because baryons contain three valence quarks and their formation is suppressed in fragmentation, recombination remains the dominant source of baryons to higher p_T than it is the case for mesons.

The recombination mechanism reveals itself in a systematic difference between the anisotropic flow patterns of mesons and baryons in semi-peripheral collisions. If the collective flow field exists at the partonic, rather than the hadronic, level the flow anisotropy for a hadron is related to the flow anisotropy $v_2^{(q)}(p_T)$ of the quarks as

$$v_2^{(M)}(p_T) = 2v_2^{(q)}(p_T/2), \qquad v_2^{(B)}(p_T) = 3v_2^{(q)}(p_T/3). \qquad (5)$$

Careful measurements for a variety of identified hadron species at RHIC have impressively confirmed the universality of quark flow [34].
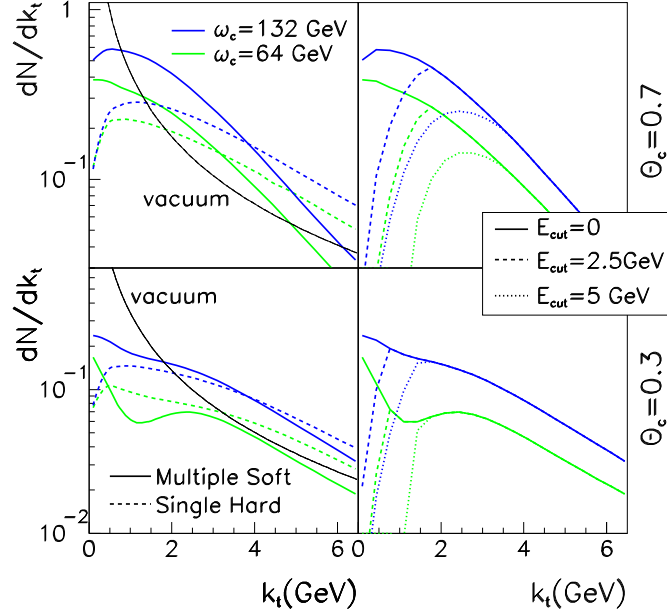
Fig. 5. Quenching effect on the particle distribution within the jet cone for two different opening angles (from [27]).

Due to the slightly increased suppression of hadrons from fragmentation and the also increased radial flow of the expanding matter, the transition point between recombination and fragmentation dominance is expected to shift to larger p_T (up to 10 GeV/c) at the LHC [35] (see Fig. 6). The capability of a detector like ALICE to identify hadrons well up into this momentum range will be a crucial prerequisite for the exploration of the physics of these hadrons, which are direct messengers from the deconfined matter. An important observable, similar as at RHIC, will be the species dependence of the elliptic flow, which is predicted to derive from a universal partonic flow pattern according to eq. (5).

2.4 Heavy quarks

Heavy quarks (c and b) will be abundantly produced in Pb+Pb collisions at LHC. These quarks can serve as useful probes of the dense matter. When the color interaction in the medium is screened at sufficiently short scales, heavy quarkonia can no longer form [36]. The required conditions for this effect have recently been reconsidered on the basis of improved lattice calculations. It has become possible to calculate the potential between a heavy quark pair in the color singlet state, which predict that the J/Ψ state should survive up to $T \approx 1.5T_c$ in quenched QCD [37]. This conclusion is supported by calculations of the spectral function of a ($c\bar{c}$)
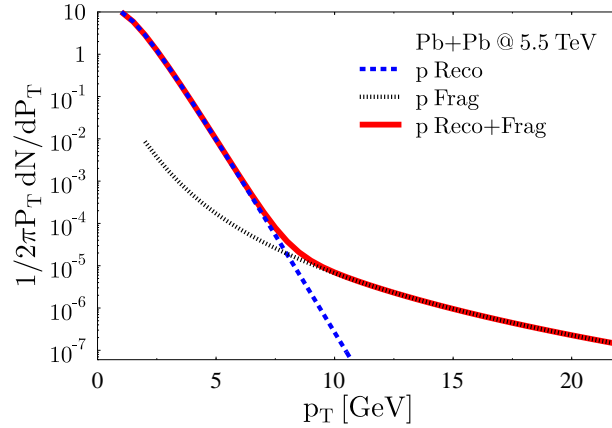
Fig. 6. Competition between recombination and fragmentation for proton emission in Pb+Pb collisions at LHC (from [35]). The calculation assumes a mean radial flow velocity $v_\perp/c = 0.75$ for the thermal component.

singlet pair, which exhibits a strong peak at the location of the J/Ψ at least up to the same temperature [38,39] (see Fig. 7). It is important to stress that these results are for quenched QCD, and may well change when dynamical light quarks are included in the lattice simulations.

On the other hand, J/Ψ and Υ states can be destroyed in the hot environment by gluon bombardment, even if the states exist [40]. Calculations predict an almost total ionization of the J/Ψ under LHC conditions and a substantial (80%) destruction of the Υ [15] (see Fig. 8). However, it is quite likely that $(Q\bar{Q})$ bound states can be reconstituted when the plasma cools [41]. While the probability for this to occur is expected to still rather small at RHIC, it will become very substantial at LHC due to the large number of created c-quarks. Formation of J/Ψ by recombination may even result in an effective charmonium enhancement in nuclear collisions [15] (see Fig. 9).

3   Summary

I have discussed several key issues of heavy ion physics at the LHC. If the experiments at the SPS have brought us a first glimpse of the quark-gluon plasma, there is every indication that enough evidence will be collected at RHIC to announce the discovery the QGP. We are not quite there yet, but the conditions for such a conclusion have come into focus [13]. Assuming that this scenario will unfold as anticipated, the LHC will become the ideal facility for a systematic exploration and quantitative confirmation of the insights obtained at RHIC, aided by the plentiful abundance of hard probes.
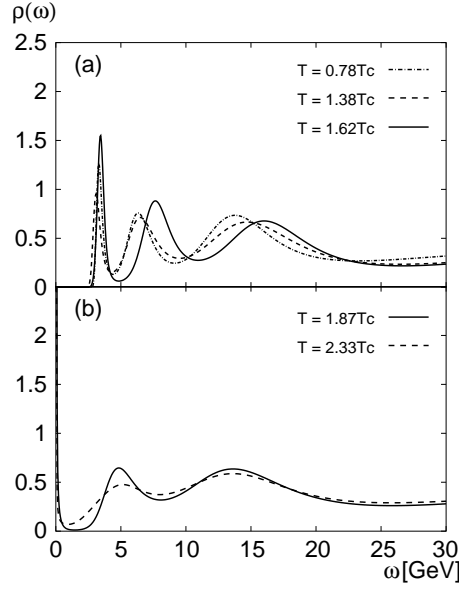
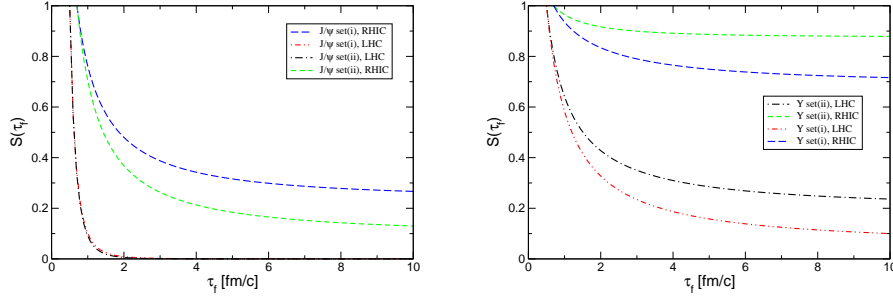Fig. 7. Spectral function in the J/Ψ channel for different temperatures below and above T_c (from [38]).

Fig. 8. Suppression of J/Ψ and Υ quarkonia at RHIC and LHC due to inization by thermal gluons (from [15]).

Some important questions, which will be at the focus of the LHC heavy ion program, are:

– How does gluon saturation work at small x? Is there a universal saturated state?

– How does parton energy loss depend on the energy density? How are fragmentation functions modified in the medium?
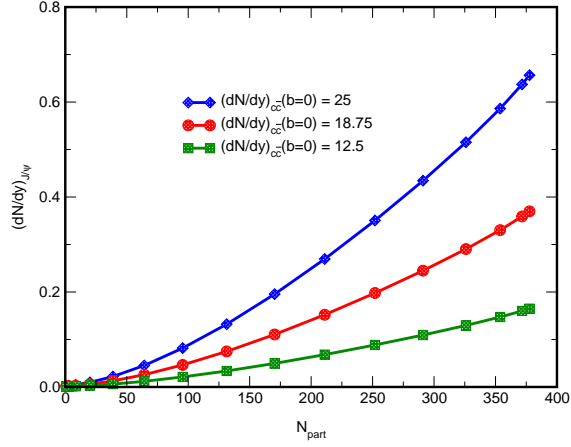
Fig. 9. Yield of J/Ψ mesons due to recombination from a thermal, deconfined quark-gluon plasma for Pb+Pb collisions at LHC for three different assumptions of the open charm multiplicity (from [15]).

– Are heavy quarks thermalized in the medium? Are they deconfined?

– What is the role of nuclear higher twist effects?

By extending the parameter range far beyond what is possible at RHIC, the LHC will be the ideal machine to yield answers to these interesting and important questions.

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